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The Big Occulting Steerable Satellite (BOSS)

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ABSTRACT

Natural (such as lunar) occultations have long been used to study sources on small angular scales, while coronographs have been used to study high contrast sources. We propose launching the Big Occulting Steerable Satellite (BOSS), a large steerable occulting satellite to combine both of these techniques. BOSS will have several advantages over standard occulting bodies. BOSS would block all but about 1.5×10^{-5} of the light at 1 micron in the region of interest around the star for planet detections. Because the occultation occurs outside the telescope, scattering inside the telescope does not degrade this performance. BOSS could be combined with a space telescope at the Earth-Sun L2 point to yield very long integration times, in excess of 3000 s. Applications for BOSS include direct imaging of planets around nearby stars. Planets separated by as little as 0.1–0.25 as from the star they orbit could be seen down to a relative intensity as little as 1×10^{-9} around a magnitude 8 (or brighter) star. Other applications include imaging of compound sources, such as microlensed stars and quasars, to a resolution well below 1 mas.

Subject headings: planets – gravitational lensing—occultations—space vehicles—stars: low-mass, brown dwarfs

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1. Introduction

The search for planets around nearby stars is a major objective of modern astronomy. Recently, astronomers have discovered Jupiter-mass planets orbiting nearby stars (see e.g., Mayor & Queloz 1995; Butler & Marcy 1996; Mayor & Queloz 1995; Cochran, et al. 1997; Marcy, et al. 1997; Noyes, et al. 1997). They observed the periodic variation in the central stars' velocities due to their motion around the center-of-mass of the star-planet systems. However, they were unable to image the planets directly—the planets are too close to the stars that they orbit, so diffraction in the telescope and atmospheric seeing cause the starlight to wash out the planets. This problem is generic to observations of compact, compound sources in which the range of brightnesses of the individual components is large.

On another forefront, many astrophysical systems have structure on milli-arcsecond or sub-milli-arcsecond angular scales. Examples include images of stars lensed by massive compact halo objects (MACHOs), binary stars, globular cluster cores, Galactic supernovae, cores of nearby galaxies, lensed images of galaxies, and distant galaxies and clusters.

The separation of dim sources from nearby bright ones, and the resolution of images at milli-arcsecond scales are limited principally by diffraction, seeing and scattering of light in the telescope. Seeing can be reduced using adaptive optics (AO) or eliminated by going to space; however, the diffractive limit of a telescope is fixed by its diameter and the observational wavelength band. While AO is typically very good at squeezing the central core of a point spread function (PSF) to near the diffraction limit, it still leaves the scattering halo of the PSF.

These combined effects make it difficult to observe most expected planetary systems from the existing Hubble Space Telescope, and a challenge even for the Next Generation Space Telescope (NGST). Greater resolution can be obtained using interferometry, and plans exist to do both ground-based and space-based IR and optical interferometry. Ground based interferometers, such as the VLTI, are most useful for high accuracy astrometry. The Space Interferometry Mission, a 10 m baseline interferometer expects to do astrometry at the microarcsecond level. It will directly detect the wobble in a star due to an orbiting Jovian planet, and perhaps even an Earth-like planet, but it will not separate the planetary light from the starlight. Very large space-based interferometers such as the Terrestrial Planet Finder are planned, but will be more challenging technologically, more costly, and require more time to build than BOSS. They could also benefit from an associated BOSS-like satellite.

The idea of the BOSS mission is to use occultations by a large satellite to achieve high resolution and high brightness contrast. Lunar occultations have long been used to resolve small-scale angular structure (see e.g., Han, Narayanan, & Gould 1996; Simon et al. 1996; Mason 1996; Richichi et al. 1996; Cernicharo et al. 1994; Adams et al. 1988). By monitoring the light-curve from an occulted source, one can measure the separation of the source components projected along the moon's velocity vector, and the relative intensity of the components.

Lunar occultations are, however, limited. The lunar orbit is fixed so sources cannot be scheduled for occultation and most sources are never occulted. The angular velocity of the Moon is large, so occultations are short. Finally, the dark side of the Moon is relatively bright, even visible to the naked eye. To escape these limitations, we propose launching a large occulting satellite. The Big Occulting Steerable Satellite (BOSS) will consist of a large occulting mask. Patch geometry and transmission function can be optimized for either high-resolution image reconstruction or separation of bright from dim sources. In this talk we will concentrate on the latter. The configuration that we consider is a square structure with a circularly symmetric transmission function that rises smoothly from zero (opaque) at the center to maximally transmissive where the inscribed circle osculates the edge of the square. The size of the inscribed circle, as will be made clear below, needs to be large, approximately 35 m in radius, so the square is approximately 70 m $\times$ 70 m. BOSS will consist of from a thin opaque film supported by a framework of inflatable or deployable struts. Appropriate films with surface densities of $\sigma \simeq 10$–20 g m^{-2} are available, and the technology for deploying large structures composed of them reliably is under active development (Chmielewski, Garner, Helms and Lichodziejewski).

BOSS would be located near L2, the second Lagrangian point of the Earth-Sun system, 0.01 AU past the Earth along the Sun-Earth line. It would be operated in concert with a large space telescope such as NGST (8-m class telescope) in halo orbit about L2. While the telescope orbited, BOSS would be positioned to cause the desired occultations. By using a combination of ion engines and sailing in the solar radiation pressure, one should be able to obtain very long integration times.

2. Locating BOSS

The criteria determining where BOSS should be located are: (1) darkest possible occultations of target stars, (2) longest possible duration occultations, (3) easiest possible multiple target acquisition, and (4) highest possible duty cycle.

The first objective, dark occultations, is the most important, as it governs the utility of BOSS in discovering planets. BOSS's efficacy is governed by its distance from the satellite, by its size, and by its optical properties. In the geometric optic limit, BOSS could completely blocks the bright stellar source. However, because of diffraction some of the starlight reaches the telescope (see the discussion in section 5). The larger the occulter, the greater the fraction of total light which is blocked, but the further the planet must be from the star not to be occulted itself (nor be contaminated by the diffracted light which is concentrated near the edge of the occulter). Consequently, one would like the occulter to be as large as possible and as far away from the telescope as possible. Using current technology an occulter up to approximately 100 m $\times$ 100 m could be constructed and deployed. Using our solar system as a template, the angular separation for planets around nearby stars is approximately 0.1 as. Thus ideally one would like a 50–100 m diameter BOSS located at a distance of order 10^4–10^5 km.

Long duration occultations are the the most important technical challenge. Since the angular size of the satellite is chosen to be comparable to the angular separation of the bright and dim sources, the time over which one can integrate on the dim source is approximately the time during which the satellite occults the bright source—essentially the time one can keep the satellite from crossing its own length. This must be long enough to allow the planet to be detected above both the associated star and any background.

These factors suggest that the second Lagrangian point (L2), located along the line from the Sun to the Earth approximately 1.5×10^6 km (0.01 AU) beyond the Earth, is an ideal location for BOSS. At L2 the gravitational force due to the Earth and Sun combine to give a period for a circular orbit of exactly one year. Near L2, there are elliptical orbits in the ecliptic and oscillatory orbits perpendicular with periods of approximately half a year. There are also unstable modes in the ecliptic of similar time constant. This instability keeps L2 relatively free of debris, and therefore a relatively safe environment.

The long periods of the orbits show that the effective gravity near L2 is quite small. At $10^{(4-5)}$ km from L2, the acceleration needed to stay stationary with respect to L2 is $a \simeq 2\times10^{-(5-6)}$ m s^{-2}. If BOSS were positioned to occult a star it would take $\mathcal{O}\left((1\text{–}3) \times 10^3\right)$ seconds to drift 10 m off-center. Orbital velocities at these radii are 4–40m/s, making it relatively easy to reposition the BOSS and to station-keep with respect to the telescope. Numerical simulations of orbits out to approximately 10^5 km, show similarly low orbital velocities and accelerations.

L2 is also advantageous because the three brightest contaminating sources (the Sun, Earth, and Moon) are in one general direction on the sky. NGST is likely to be deployed in a halo orbit around L2. Deployment of BOSS in conjunction with a space telescope at or near L2 is thus quite attractive.

3. Satellite Configuration

How large must BOSS be?

One constraint is that BOSS must be large enough that scheduled occultations occur despite the uncertainty, $\Delta\delta$, in the source location on the sky. Although Hipparcos determined the relative stellar positions to about 1 mas, the global uncertainty was about $\Delta\delta \lesssim 0.1$ as, and is increasing with time. Fortunately, the Hipparcos catalogue will likely be supplemented by the SIM catalogue before the BOSS launch date. SIM should provide absolute angular positions for the target stars with better than $\Delta\delta \lesssim 0.01$ as accuracy. We require that the BOSS be large enough to subtend a solid angle greater than the uncertainty in its desired position. If $r \leq 10^8$ m and $\Delta\delta = 0.01$ as, then $r\Delta\delta \simeq 5$ m. A combination of telemetry and analysis of the stellar diffraction pattern should allow us to determine BOSS's position to 5 m or better in real time.

Even if we can know where the satellite should be and where it is very accurately, can we place it where it is needed when it is needed with the appropriate velocity? That question is difficult and is currently unanswered, but the answer is not obviously no. Relevant effects include solar radiation pressure, lunar gravity, eccentricity of the Earth's orbit, etc., all of which need to be understood to address this question.

Also influencing the choice for BOSS's size is the diffraction of light around the satellite. The larger BOSS is, the more light it blocks, but the further away on the sky the planet source must be from the star not to be occulted. For high resolution imaging, there is less of a constraint since the diffraction limit for the satellite is independent of the size of the satellite if $\lambda < x^2/r \simeq 500\ \mu$m.

We will use $R_{\rm BOSS} = 35$ m for BOSS in this paper, though further characterization of BOSS performance as a function of size is essential and ongoing. The optimum answer will depend on the exact observing program and the nature of the objects to be occulted. A 70 m $\times$ 70 m square occulter made of 0.3 mil clear polyimide supported by rigidized struts, would be as little as 200 kg. Since skin depths of good conductors in optical and IR bands are very much less than a micron, the occulter can be as opaque as needed. Detailed calculations of the expected survival lifetime of the struts and occulting film are essential, as is the evolution of film optical properties with time in the high radiation environment.

The square geometry is not actually optimal. As we discuss below, minimization of diffractive losses suggests that a circular satellite is preferred. However, supporting a circle using an (opaque) toroidal ring leads to severe degradation in optical performance unless the ring is extremely thin. A square occulter supported by diagonal struts, with an inscribed, circularly symmetric transmission function is what we consider.

The transmission function of the occulter would be designed to rise from zero near the center to its maximum possible value near the edge. As discussed below, this variable transmission function lowers the amount of light focussed behind the satellite. Spacecraft systems would be mounted behind the opaque center of the occulter, except for ion engines which would be mounted at the ends of the struts.

4. Maneuvering Boss

To alter BOSS's orbit requires imparting an impulse, $\Delta \boldsymbol{p} = m \Delta \boldsymbol{v}$, resulting in a change of velocity

$$\frac{\Delta \boldsymbol{v}_{\rm sat}}{v_{\rm sat}} = \frac{\Delta m_{\rm propellant} \boldsymbol{v}_{\rm ejection}}{m_{\rm sat} v_{\rm sat}} \tag{1}$$

The number and magnitude of orbital maneuvers will probably determine BOSS's lifetime. For a satellite lifetime of 5 years, and assuming we can reposition BOSS once or twice a day $N = \mathcal{O}(3 \times 10^3)$ is a reasonable estimate of the number of major orbital maneuvers. If $\Delta m_{\rm propellant}$ is the typical mass of propellant expended per maneuver, then we must keep $(\Delta m_{\rm propellant}/m_{\rm sat}) \leq N^{-1}$. This implies that

$$v_{\rm ejection} \geq N \Delta \boldsymbol{v}_{\rm sat} \tag{2}$$

As discussed above, satellite orbital velocities are in the range 4–40 m s^{-1} for the orbital radii of interest. If in each maneuver $\Delta \boldsymbol{v}_{\rm sat} \simeq v_{\rm sat}$, then $N \simeq 3000$ maneuvers requires $v_{\rm ejection} \simeq$ 12–120 km s^{-1}. With careful scheduling, and clever orbital dynamics, typical course corrections might not require $\Delta \boldsymbol{v}_{\rm sat} \simeq v_{\rm sat}$.

Off-the shelf, low-cost ion engines are currently available with ejection velocities of 20 km s^{-1}, and more expensive systems with 30 km s^{-1} performance have been developed (Garner). These engines develop approximately 0.1 kg m s^{-2} of thrust, enough to generate an acceleration of 10^{-4} m s^{-2} for a 10^3 kg satellite.

Solar radiation pressure will also play a significant role in determining the satellite's motion. This can either be viewed as a problem or an opportunity. In the vicinity of L2 the solar pressure is approximately 4×10^{-6} N m^{-2}. For a satellite of effective surface density 0.05 kg m^{-2}, this produces an acceleration of 8×10^{-5} m s^{-2}, though this can be reduced by maintaining BOSS at an oblique angle to the sun. Thus solar sailing could play some role in maneuvering BOSS. Of course, the solar radiation pressure is pushing away from the sun, so of solar sailing alone will not suffice to maneuver BOSS.

5. Diffraction

Because we are interested in observing systems with very high contrast, we must include the effects of diffraction. The angular width of the satellite diffraction pattern in the region far from the satellite is

$$\Delta\theta_{\rm diff} \simeq \begin{cases} \frac{\lambda}{2R} & \text{if } \frac{\lambda}{2R} \geq \frac{x}{D_{\rm sat}} \text{ (Fraunhoffer limit)}, \\ \left(\frac{\lambda}{D_{\rm sat}}\right)^{1/2} & \text{if } \frac{\lambda}{2R} \leq \frac{2R}{D_{\rm sat}} \text{ (Fresnel limit)}. \end{cases} \tag{3}$$

Here $2R$ is the diameter of the occulter. The transition from Fresnel to Fraunhoffer behavior occurs for $2R \simeq \sqrt{\lambda D_{\rm sat}} \simeq 10$ m, for $\lambda \simeq 1\ \mu$m and $D_{\rm sat} \simeq 1 \times 10^8$ m.

Inspection of (3), shows that once the size of the satellite has reached $\sqrt{\lambda D_{\rm sat}}$ no further reduction in $\Delta\theta_{\rm diff}$ is obtained by increasing R. However, the fraction of the intensity of the occulted source which is not blocked decreases with the area of the occulter. For this reason, we choose a large value of $R = 35$ m.

Our problem includes double diffraction since we must first calculate the electromagnetic field amplitude as a function of position in the telescope aperture, and then use that to calculate the amplitude at each pixel in the focal plane detector. This calculation must be repeated for every source position and at every wavelength of interest. In calculating the amplitude of the light at the telescope aperture, we find that we must keep terms of order $k\xi^2/2R_{\rm BOSS} > 1$ where ξ is a dimension in the occulter plane. The presence of this higher order term means that we are working in the Fresnel limit of diffraction. The field is therefore highly oscillatory, as is the resulting amplitude.

The calculation of a simulated image is therefore very challenging. Straightforward numerical integration requires many hours to produce a single image. Using a scheme in which $U_{\rm mask}$ is expanded in Tchebyshev polynomials we are able to evaluate all the integrals analytically and express the result as a sum over Bessel functions which can be evaluated numerically. A complete image of an arbitrarily located point source can thus be obtained in only a few minutes.

By manipulating the transmission function in the occulter plane, we are able to apodize the diffraction pattern of the occulted star caused by the satellite. We use this to make the prospective planetary regions darker. For the transmission function we follow the preliminary analysis of Hyde (1998, private communication) and focus on the fourth occulter

$$\tau_4(y) = 35y^4 - 84y^3 + 70y^6 - 20y^7, \tag{4}$$

Here y is a function of the radius r,

$$y = \frac{\left(\frac{r}{R_{\mathrm{BOSS}}}\right)^2 - \epsilon}{1-\epsilon} \tag{5}$$

ϵ is the fractional radius within which the occulter is completely opaque ($\tau = 0$). Throughout this work we will consider $\epsilon = 0.15$. This transmission function was obtained by minimizing the on-axis intensity of an on-axis occulted star. Though this criterion is not optimal for planet detection, it provides a simple function that improves performance and can be used as a starting point for future investigations.

We should also note that real materials do not have perfect transmission. In the near IR it is possible to get 97% transmission in a film with an anti-reflective coating. Thus we will replace τ with $(1-\delta)\tau$ and consider $\delta = 0.03$. We will also use a constant transmission function of $1-\delta$ for the square in which our circular pattern is imprinted. Smaller values of δ, if achieved, could lead to improvement in the performance of the BOSS.

6. The Satellite as a Source

Just like a planet, BOSS would shine by reflection, both coherent and diffuse, and by thermal emission. A serious concern is that BOSS might appear brighter than the sources it is occulting and thus be of little value. The situation is particularly complicated by apodizing the occulter since some sunlight will be scattered in the portions of the occulter which are not completely opaque.

We consider first the flux of reflected sunlight. reflected by a patch of area A_{patch} with albedo $\mathcal{A}$ and collected by a telescope of diameter $2R_{\mathrm{tel}}$, a distance D_{BOSS} from the occulter. Compare this to the rate of photons received in the telescope from an 8m star suppressed by 10^{-3}—the approximate BOSS brightness at which the ability to identify planets begins to degrade. We find that BOSS is sufficiently dim if

$$A_{\mathrm{patch}} \leq \frac{0.77\ \mathrm{mm}^2}{\mathcal{A}} \left(\frac{T_\odot}{T_\star}\right) \left(\frac{D_{\mathrm{BOSS}}}{1\times 10^8\ \mathrm{m}}\right)^2 \tag{6}$$

This is a strenuous requirement implying that careful attention must be given to the shape and orientation of BOSS's exposed surfaces including its edges. However, it is reassuring that the Sun subtends only 6.8×10^{-5} steradians, or 5.4×10^{-6} of the sky. Random fluctuations of the occulter surface are therefore unlikely to reflect light into the telescope. So long as we are careful to appropriately orient the satellite and control the fluctuations in the surface we should be able to meet this specification.

Some of the sunlight will pass through the transmissive portions of the occulting body and be scattered diffusely. Let $\mathcal{S}$ be the fraction of photons that are scattered diffusely. Assuming isotropic scattering, the flux of photons at the telescope resulting from diffuse reflection from the satellite will be less than the flux of a star of bolometric magnitude m_b suppressed by a factor of $\epsilon \simeq 10^{-3}$ requires

$$\mathcal{S} < 0.3\epsilon \left(\frac{D_{\rm BOSS}}{1 \times 10^8 \text{ m}}\right)^2 \left(\frac{A_{\rm BOSS}}{(70 \text{ m})^2}\right)^{-1} \left(\frac{T_\odot}{T_\star}\right) 10^{-0.4(m_b^\star - 8)}. \qquad (7)$$

The diffuse scattering of light in transparent films, such as polyimides, which might be used for BOSS has been studied. For a 10 μm film $\mathcal{S} < 10^{-5}$ at 1 μm is not unusual (e.g. Kowalczyk, et al. 1994).

Finally, thermal emission arises because BOSS is warmed by the sun. If the satellite comes into thermal equilibrium with the solar radiation then

$$T_{\rm BOSS} \simeq 332 \text{ K} \left(\frac{\alpha}{e}\cos\theta\right)^{1/4}. \qquad (8)$$

where α is the fraction of incident solar radiation energy absorbed, $90^\circ - \theta$ is the angle between the sun and the normal to the plane of the occulter, and e is the emissivity. For many materials $\alpha/e \sim 2$, but typically during observations θ will be greater than 60°, so $\alpha\cos\theta/e$ should not be large.

Comparing the flux from the warm satellite to the flux from an occulted star in the same waveband we find that observations at wavelengths shorter than 1.5–2.0 μm are unlikely to be seriously affected by the thermal emissions from BOSS. Wavelengths longer than 2.0 μm are seriously affected.

Allowing the satellite to be as bright as a magnitude 15.5 star does not limit us to resolving pairs of magnitude 15.5 objects since it is the shot noise in the flux from the satellite that limits the resolution. For $T_\star = T_\odot$ and a 1 s exposure (the typical time it takes a satellite orbiting L2 to cross 0.1 mas), a 23.7 bolometric magnitude target star would give $\frac{\sqrt{N_{\rm BOSS}}}{N_\star} \simeq 1$. It thus should be relatively easy to differentiate between stars of magnitude 20 or more at separations of better than 0.1 mas. A preliminary analysis confirms this intuition.

7. Planet Searches

Planets shine in two ways, in reflected light and in emitted light. In reflected light, the brightness of a Jupiter-like planet orbiting 1 AU from a star is about 3×10^{-8} times that of the star; falling off as $1/r^2$ as the orbital radius increases, but growing as the radius of

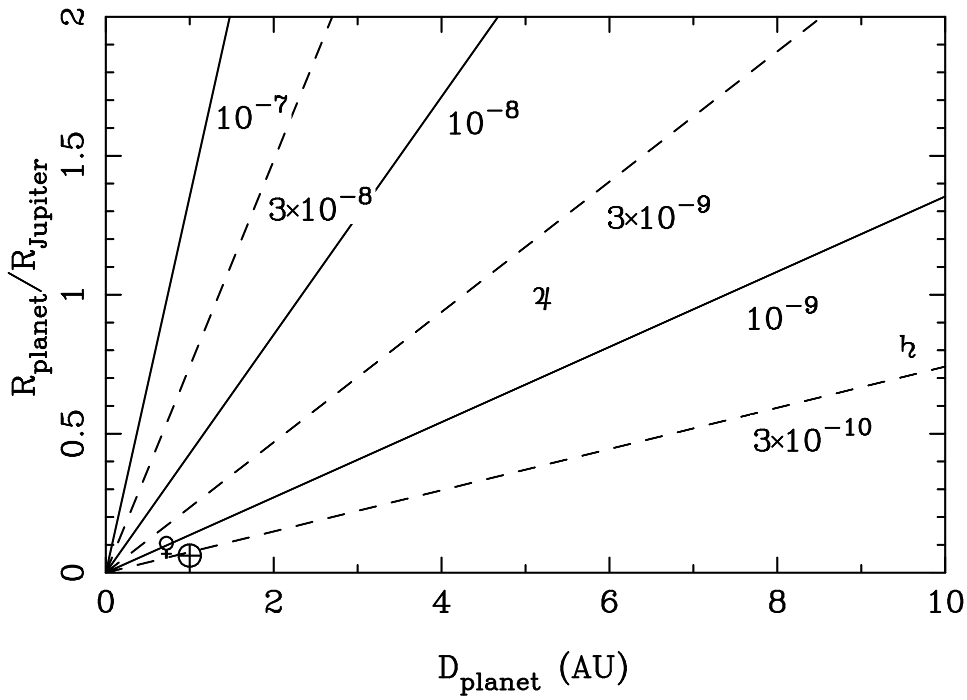

Fig. 1.— The detection capability of a planet with BOSS as a function of a planet's size and distance from the star. The curves show the relationship between the size of a planet and its distance from a star for relativity intensities of 10^{-7}, 3×10^{-8}, 10^{-8}, 3×10^{-9}, 10^{-9}, and 3×10^{-10}. Here we have assumed the factor combining the albedo, phase angle, and illuminated fraction of Jupiter is equal to one. For a given detectable relative intensity (for example 3×10^{-9}) all planets above this curve would be detectable. Also shown in this figure are the brightest planets in our solar system (from left to right using their standard symbols), Venus, Earth, Jupiter, and Saturn. We have plotted the planets using an effective radius that includes their albedo relative to Jupiter so that the relative intensity curves are scaled the same for all the planet.

planet squared (see figure 1). In emitted light, a planet glows as approximately a black body characterized by its temperature, though molecular absorption can alter that dramatically in certain wavebands. A planet's temperature is a strong function of its age, the central star's type and proximity, atmospheric composition, and internal heat sources (see e.g., Burrows et al. 1997); however, the emission spectrum for most planets peaks at very long wavelengths ($\gtrsim 10$ μm). We will focus on a 1 micron wave band (0.9–1.1 μm) for our studies since the diffraction from an 8-m telescope is not too severe in this waveband. At this waveband thermal emission from the planet is far too small to be of interest, and we will consider exclusively reflected light.

To study the benefits of employing BOSS in conjunction with a space telescope we have simulated the images produced by our solar system at 3 pc and 10 pc occulted by BOSS and viewed by a 8-m telescope. For our solar system we have included the Sun occulted on-axis and the four brightest planets; Venus, Earth, Jupiter, and Saturn. We have used the BOSS configuration described in section 3 and have assumed that BOSS is located 10^8 m from an 8-m space telescope at L2. All images have been calculated for the 1 μm waveband. Images of the occulted star and unocculted planets are calculated for 3 different wavelengths in this waveband in the manner described in section 5. The telescope point spread function (PSF) we employ has a diffraction limited core and a Gaussian halo with a 1 as FWHM that contains 10^{-3} of the light. Because diffraction by the telescope is already included, the images are smoothed with the halo component of the PSF. The smoothed images provide the templates of the occulted star and unocculted planets. From these templates we can construct an image of a solar system. We first scale the planets' intensities by the appropriate fraction of the unocculted star's intensity. To account for uncertainties in the PSF, we then include a Gaussian random component equal to 5% the intensity of each pixel. After adding the planets to the occulted star, we Poisson sample the resulting image to produce a simulated image of the solar system. To identify planets, the template of the occulted star is subtracted, leaving behind the planets and the noise. A planet is detectable if it can be identified above this noise.

Table 1. Parameters for our Solar System

					Angular Separation (as)		
Planet	Radius ($R_{\rm Jup}$)	Distance (AU)	Albedo	Flux ($\Phi_\odot$)	3 pc	5 pc	10 pc
Venus	0.087	0.72	0.76	1.2×10^{-9}	0.24	0.14	0.07
Earth	0.091	1.00	0.39	3.4×10^{-10}	0.33	0.20	0.10
Jupiter	1.000	5.20	0.51	2.0×10^{-9}	1.73	1.04	0.52
Saturn	0.837	9.56	0.50	4.0×10^{-10}	3.19	1.90	0.95

Note. — For each planet the radius is given in units of Jupiter's radius, the distance from the Sun is given in AU, and the flux of reflected light is given relative to the flux of the Sun. The angular separations are given for the solar system at 3 pc and 10 pc from BOSS.

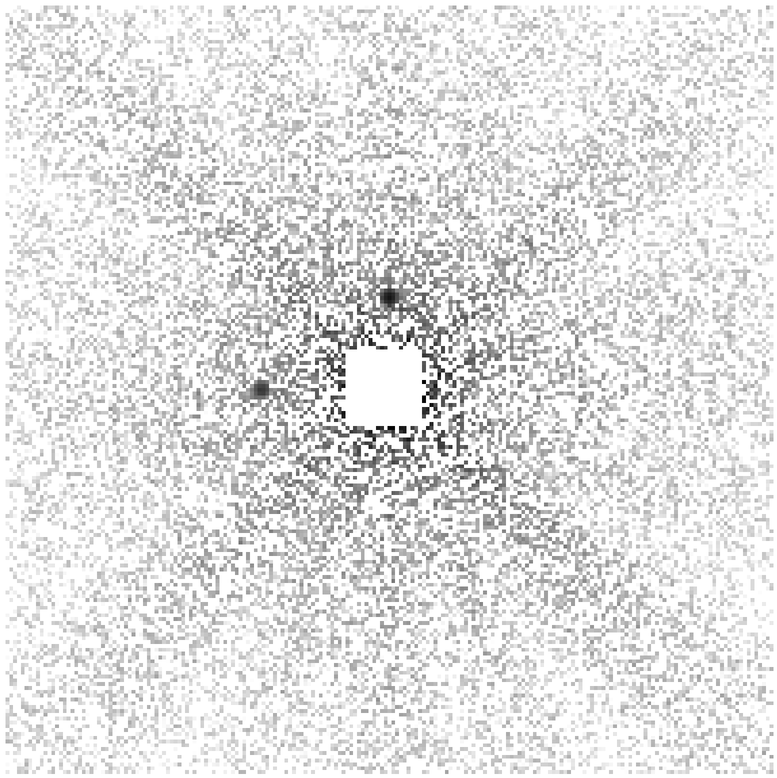

Fig. 2.— A 2 as by 2 as CCD image of the log of the intensity for our our solar system at 3 pc from BOSS as observed in the 1 μm waveband by an 8-m space telescope. The Sun at this distance has a bolometric magnitude of $m_b^{\odot} = 2.1$ and is located at the center of the satellite. The central 0.2 as square (roughly the size of BOSS) has been cut out of the image. Both Venus (above) and the Earth (left) are marginally observable. Jupiter and Saturn are easily detectable but are outside the field of view of this image.

Figures 2 and 3 show our solar system in reflected light, 3 pc and 10 pc away from us, respectively. The parameters describing out solar system are given in table 1. The bolometric magnitude of the Sun at 3 pc is $m_b^{\odot} = 2.1$ and at 10 pc is $m_b^{\odot} = 4.72$. The images are 2 as $\times$ 2 as CCD images with 0.01 as $\times$ 0.01 as pixels. The central 0.2 as square (roughly the size of BOSS) has been cut out. At 3 pc, Venus and the Earth are just visible by-eye. Both Jupiter and Saturn would be easily observable but are outside the CCD shown here. At 10 pc Venus and the Earth are occulted by BOSS but both Jupiter and Saturn are easily identified.

The relative intensity for Jupiter given in table (1) and used in these figures was calculated using its Bond albedo and assuming uniform scattering into 2π steradians. The intensity for the rest of the planets are scaled from Jupiter using their size, distance, and

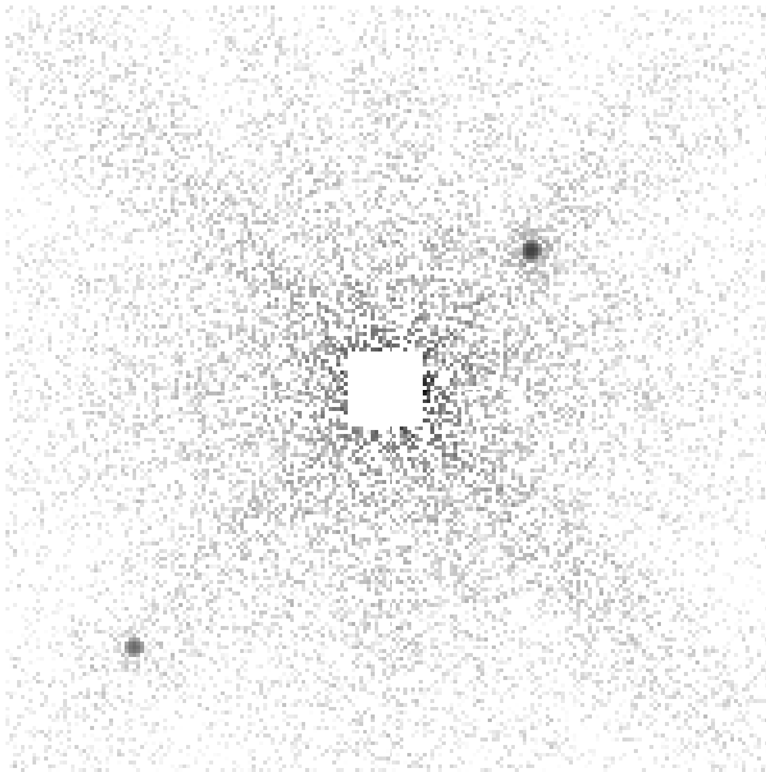

Fig. 3.— A 2 as by 2 as CCD image of the log of the intensity for our our solar system at 10 pc from BOSS as observed in the 1 μm waveband by an 8-m space telescope. The Sun at this distance has a bolometric magnitude of $m_b^{\odot} = 4.72$ and is located at the center of the satellite. The central 0.2 as square (roughly the size of BOSS) has been cut out of the image. Both Venus and the Earth are occulted by BOSS. Jupiter (upper right) and Saturn (lower left) are easily detectable.

albedo relative to Jupiter. We should also note that many improvements can be made in the analysis described above. A statistical image reconstruction technique could more reliably detect planets and may allow for identification of planets that the "by-eye" technique misses. Also, the reflected light from a planet would be polarized whereas starlight is not. Thus even further suppression of the starlight should be possible. Finally we comment that the 1 μm waveband is a fairly good choice for gas giant planets. Although CH_4 (which is prevalent in gas giant atmospheres) has an absorption feature at 1 μm, it is fairly weak and sufficient flux comes from the two edges of the waveband to compensate for this. Above about 1.1 μm strong CH_4 absorption dominates the spectrum and drastically reduces the intensity of reflected light.

8. Conclusion

Occultations provide a powerful technique for resolving both small angular scales and large separations in intensity. BOSS will offer distinct improvements over a lone space telescope allowing it to directly image planets. BOSS blocks all but 1.5×10^{-5} of the light from a star in the 1 μm waveband. Furthermore, by doing the occultation well outside the telescope degradation due to scattering inside the optics is avoided. The low effective gravity at L2 offers the possibility of obtaining very long exposures.

In this work we have shown that a 70 m $\times$ 70 m BOSS in conjunction with an 8-m space telescope at L2 would allow for the direct imaging of Venus, Earth, Jupiter, and Saturn at 3–5 pc. Both Jupiter and Saturn would be visible out to about 25 pc. Solar systems with Jupiter-like planets closer to their star would be easily observable. Furthermore, photometric and spectrographic observations could be considered for these objects.

In addition, angular resolution of compound sources of comparable brightness down to below 0.1 mas is feasible, although we have not explored this in detail here.

Many improvements can be made over the techniques employed here to aide in finding dim planets. A sophisticated reconstruction technique would greatly improve the "by-eye" technique presented here. Also using polarized light from the planet versus the unpolarized light from the star would significantly increase the separation of planets from the star. In spite of the simple techniques used here BOSS has been shown to be a powerful tool for discovering and imaging planets.

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